# A Statistical Measure for the Sharpness of the SEM Images[1,2]

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## ABSTRACT

Fully automated or semi-automated scanning electron microscopes (SEM) are now commonly used in semiconductor production and other forms of manufacturing. Testing and proving that the instrument is performing at a satisfactory level of sharpness is an important aspect of quality control. The application of Fourier analysis techniques to the analysis of SEM images is a useful methodology for sharpness measurement. In this paper, a statistical measure known as the multivariate kurtosis, is proposed as a useful measure of the sharpness of SEM images. Kurtosis is designed to be a measure of the degree of departure of a probability distribution from the Gaussian distribution. It is a function of both the fourth and the second moments of a probability distribution. For selected SEM images, the two-dimensional spatial Fourier transforms were computed. Then the bivariate kurtosis of this Fourier transform was calculated as though it were a probablility distribution, and that kurtosis evaluated as a characterization tool. Kurtosis has the distinct advantage that it is a parametric (i.e., a dimensionless) measure and is sensitive to the presence of the high spatial frequencies necessary for acceptable levels of sharpness. The applications of this method to SEM metrology will be discussed.

**Key Words:** Image Analysis; Fourier Transform; Metrology; Kurtosis; Scanning Electron Microscope; Sharpness

## 2. INTRODUCTION

The industrial users of scanning electron microscopes would like to have these instruments function without human intervention for long periods of time, and to have some simple criterion (or indication) of when they need attention. At the present time, no self testing is incorporated into these instruments to verify that the instrument is performing at a satisfactory performance level. Therefore, there is a growing realization of the need for the development of a procedure for periodic performance testing. A degradation of the sharpness of the image of a suitable test object can serve as one, of perhaps several, simple indicators of the need for maintenance. A procedure based on this sharpness principle was suggested by Postek and Vladar,[9] and it has subsequently been refined into a user-friendly stand-alone analysis system.[10] Their suggestion was based on the objective characterization of the spatial Fourier transform of the SEM image of a test object rather than on subjective visual evaluation of that image. Recent follow-on work at NIST has concentrated on the identification of suitable test objects for this purpose and the development of appropriate analytical algorithms for characterizing sharpness. In this paper, a statistical measure, known as the multivariate

kurtosis, is proposed as one approach to the measurement the sharpness of SEM images. This paper also discusses the criteria for selection of test objects that are most appropriate for this technique, and illustrates the results obtained when this technique is applied to actual SEM images of the recommended type of test sample.

## 3. MATERIALS AND METHODS

**3.1 Scanning Electron Microscope.** The scanning electron microscope used in this study was a laboratory Hitachi[2] S-4500 cold field emission scanning electron microscope (FESEM).

**3.2 Sample.** The most appropriate sample identified so far, as a standard sample for the analysis of sharpness is an etched silicon wafer with the artifact referred to as "grass." Grass is an etching artifact which can occur on silicon wafers during processing[8]. Commonly, this effect is avoided. However, for the measurement of sharpness, such a sample is ideal. This sample is conductive and can be used at either high or low accelerating voltage. The particular sample used in this work was made at Texas Instruments, Inc. by Dr. Brian Newell during the fabrication of RM 8090, the new NIST SEM magnification standard. The grass is a result of a surface masking during the reactive-ion-etching process and, where this particular sample is concerned, resulted in random fine structures approximately 3-10nm in size.

**3.3 Univariate and Multivariate Kurtosis.** In the theory of probability, kurtosis is a measure of a type of departure of a probability distribution from the normal (Gaussian) shape. For a given univariate random variable X with mean $\mu_x$ and finite moments up to at least the fourth, the kurtosis is defined by Kotz and Johnson:[6]

$$\beta_2 = \gamma_4/\gamma_2^2, \tag{1}$$

where $\gamma_4$ and $\gamma_2$ are the fourth and second central moments respectively, i.e.,

$$\gamma_4 = E[(X - \mu_x)^4] \quad \text{and} \quad \gamma_2 = \sigma_x^2 = E[(X - \mu_x)^2], \tag{2}$$

where E denotes the probability expectation of a random variable. For any univariate normal distribution, $\beta_2 = 3$. Therefore, the value of $\beta_2$ can be compared with 3 to determine whether the distribution is "peaked" or "flat-topped" relative to a Gaussian. It should be noted that kurtosis is often quoted as $(\beta_2 - 3)$ and that $\beta_2$ is a dimensionless ratio.

Four separate distribution density functions with zero mean and unit variance were compared by Kaplansky[5] to illustrate the properties of kurtosis. His results show that the smaller the kurtosis, the flatter the top of the distribution. Finucan [4] also discussed the interpretations of kurtosis.

Based on the computed spatial frequency spectrums of selected SEM images, we observe that when an SEM image is visually sharper than a second image, the higher spatial frequency components of the first image are larger than that of the second. Treating the normalized spectrum as a probability density function, a sharper SEM image corresponds to a spectrum which has a larger shoulder or has a flatter

shape. From Kaplansky,[5] it can be concluded that the corresponding kurtosis of the sharper image is smaller. Therefore, an increase in kurtosis over some pre-established reference value, portends that the sharpness of an SEM image has been degraded relative to that existing at the time the reference value was established.

Note that, since kurtosis is a dimensionless ratio of the moments, the factor which is used to normalize the spectrum of the SEM image to make it more nearly resemble a probability density function is canceled. In fact, a value of kurtosis can be calculated for any positive valued function when the area underneath the curve is finite and when the curve has finite moments up to and including the fourth. Let $y = f(x)$ be such a discrete univariate function with $y_i = f(x_i)$ $(i=1,...,n)$. Then

$$\beta_2 = \Sigma_{i=1,n} [(x_i - \mu_x)^4 f(x_i)]/[\Sigma_{i=1,n} (x_i - \mu_x)^2 f(x_i)]^2, \tag{3}$$

where

$$\mu_x = \Sigma_{i=1,n} x_i f(x_i).$$

The corresponding multivariate kurtosis has been proposed by Mardia.[7] Let $W$ be a p-dimensional random vector with finite moments up to at least the fourth. Let $\mu$ be the mean vector and $\Sigma$ be the covariance matrix of $W$. The kurtosis of $W$ is defined by

$$\beta_{2,p} = E\{(W - \mu)^T \Sigma^{-1} (W - \mu)\}^2, \tag{4}$$

where T denotes the transpose of a vector. When $p = 1$, $\beta_{2,1}$ becomes the univariate kurtosis $\beta_2$ in (1). When $p = 2$, for a two-dimensional random vector $W = (X,Y)^T$. The marginal (i.e., one dimensional) means, marginal standard deviations and covariance are

$$\mu_x = E[X]$$

$$\mu_y = E[Y]$$

$$\sigma_x^2 = \gamma_{2,0} = E[X - \mu_x]^2$$

$$\sigma_y^2 = \gamma_{0,2} = E[Y - \mu_y]^2$$

$$\sigma_{xy}^2 = \gamma_{1,1} = E[(X - \mu_x)(Y - \mu_y)].$$

The two-dimensional kurtosis is

$$\beta_{2,2} = [C_{4,0} + C_{0,4} + 2 C_{2,2} + 4 \rho(\rho C_{2,2} - C_{1,3} - C_{3,1})]/(1 - \rho^2)^2, \tag{5}$$

where

$$C_{4,0} = E[(X - \mu_x)^4]/\sigma_x^4 \tag{6}$$

$$C_{0,4} = E[(Y - \mu_y)^4]/\sigma_y^4 \tag{7}$$

$$C_{2,2} = E[(X - \mu_x)^2(Y - \mu_y)^2]/\sigma_x^2\sigma_y^2 \tag{8}$$

$$C_{1,3} = E[(X - \mu_x)(Y - \mu_y)^3]/\sigma_x\sigma_y^3 \qquad (9)$$

$$C_{3,1} = E[(X - \mu_x)^3(Y - \mu_y)]/\sigma_x^3\sigma_y \qquad (10)$$

and $\quad \rho = \sigma_{xy}^2/[\sigma_x\sigma_y].$ (11)

In particular, when a two-dimensional random vector $W = (X,Y)^T$ has a discrete probability distribution $f(x_i, y_j)$ $i=1,...,n$ and $j=1,...,m$, the marginal means can be calculated by

$$\mu_x = \sum_{i=1}^{n} x_i \sum_{j=1}^{m} f(x_i, y_j). \qquad (12)$$

and

$$\mu_y = \sum_{j=1}^{m} y_j \sum_{i=1}^{n} f(x_i, y_j). \qquad (13)$$

The moment $\gamma_{kl}$ $(k,l = 0,1,2,3,4)$ is calculated by

$$\gamma_{k,l} = \sum_{i=1}^{n} \sum_{j=1}^{m} (x_i - \mu_x)^k (y_j - \mu_y)^l f(x_i, y_j) \qquad (14)$$

The two-dimensional kurtosis can be obtained by (5). From (14), the marginal kurtoses of the marginal distributions of X and Y are

$$\beta_{2,x} = \gamma_{4,0}/\gamma_{2,0}^2 \quad \text{and} \quad \beta_{2,y} = \gamma_{0,4}/\gamma_{0,2}^2. \qquad (15)$$

The marginal kurtosis is used to measure the shape of the marginal distribution. The difference between the marginal kurtoses can be used to detect possible instrument vibration. We used $[\beta_{2,x} - \beta_{2,y}]/\beta_{2,y}$ to measure the difference when $\beta_{2,x} \geq \beta_{2,y}$.

## 4. RESULTS

**4.1. Characterizing SEM Performance.** The image or the linescan that is viewed or measured in the scanning electron microscope is determined by a number of contributing factors. It is more than just an electron beam scanning across a surface. Some of the more important factors contributing to the properties of the SEM image are listed in Table 1. If not optimized, these factors can contribute to a degradation of an SEM image compared to a conceived ideal.

In determining the need for maintenance, it is impossible to separately consider all the contributing factors

which can degrade the performance of the SEM. However, it is possible to monitor a collection of factors as a group and characterize their combined degradation in a measure of "image sharpness" compared to some point in time when the instrument was performing satisfactorily (e.g., following a service routine). The SEM can be expected to deviate from this ideal (e.g., to degrade in time) because some of the contributing factors degraded (i.e., focus, astigmatism) while others remain constant (e.g., electronic contributions). Other factors can change rapidly or abruptly (e.g., vibration and induced fields) and monitoring additional measures of these factors would also be of interest.

For practical reasons, it is important that any useful test of performance procedure be simple, inexpensive and rapid. It is desirable that the result of such a procedure be expressed as a single characterizing number, be robust, and be interpretable as a "needs attention" or "does not need attention" number. Therefore, we will construct a measure of performance based on a numerical relative measure of sharpness based on the first three components found in Table 1. In the course of this work, it was demonstrated that information regarding fixed-pattern noise induced in the SEM image and the effects of vibration can also be deduced with this method.[9]

**4.2 Recommended Characterization**. The detrimental effects of the first three factors of Table 1 on instrument sharpness (and its isotropy) are more easily quantized in the two-dimensional Fourier transform of an image rather than in the image itself. This approach was first recommended by Dodson and Joy[3] and was applied by Postek and Vladar[9] to the production environment. A user-friendly stand-alone analysis system is undergoing parallel development,[10] and the algorithm developed in this work will be applied to that system.

**4.3 Criteria for Target Selection**. A good deal of discussion has centered around the proper test object to use in the SEM for the determination of performance. Clearly, people in semiconductor production would prefer to use their product. The use of product may prove to be acceptable in some cases, but may not be the best choice. Perhaps the ideal test object to use in the SEM for characterization of sharpness is one that would inherently produce a white noise-like spectrum of signal to the SEM detector (i.e., white noise up to some limiting frequency that is well beyond the limitations of the SEM). In this case, the upper high frequency response of this SEM video output signal would be a direct measure of maximum attainable sharpness of images produced by that SEM. However, no such white noise test object has been identified yet.

Another choice would be a test object consisting of many randomly-oriented, near-circular, sharp-edged, electron-emitted spots on a non-emitting background (i.e., high contrast). If there were a sufficiently large number of such spots visible at high magnification, their individual anisotropies would average out if viewed collectively (as is done when their collective image is Fourier transformed). If the edge is sufficiently sharp, the degradation of the SEM video signal at high spatial frequencies would be due to the SEM and not the spots and, therefore, the observed high-frequency behavior could serve as a measure of the sharpness limitations of the SEM.

Gold-on-carbon,[8] the traditional test specimen (or target), meets some of these criteria. However, as commonly prepared, there are usually many larger-sized gold particles and, at high magnification, their inevitable noncircular shape will not average out (because there are too few of them). Not averaging out

means that any observed anisotropy could be due to either the target, the SEM, or both. In addition, the results of any evaluation of sharpness using such a target may vary as the region of the target actually used is varied (e.g., to avoid the effects of contamination during previous evaluations). In addition, the perimeter-to-area ratio (high-to-low spatial frequency components) of the larger particles is low compared to a target containing only many smaller particles.

In summary, our work has shown that a sample having the following characteristics seems to be the most appropriate:

1.    The target should contain many small bright areas with sharp edges randomly positioned against a dark background with sharp edges to adequately exercise resolution. The fine-structure should be small enough to have many areas at the desired magnification, to have a net large perimeter/area ratio, and to provide averaging of their almost certain noncircular shapes in the Fourier domain.

2.    The target should exhibit uniformity of average size, distribution, and shape over large area so that a different area can be used for each test if desired (e.g., for contamination reasons).

3.    The target should be electrically conductive and be capable of withstanding the electron bombardment.

Etching silicon sometimes produces a normally undesirable result called "grass"[8] which does, in fact, consist of a large number of small spot-like structures 3-10 nm in size (Figure 1). Since this target appears to meet the current needs and is potentially conductive, it was used for the demonstrations of sharpness evaluation for this paper.

**4.4 Analyses of the two-dimensional discrete Fourier Transform (FT) of the Target Image.** Once an SEM image of the test object has been obtained, the next step is to compute its two-dimensional Fourier transform (FT) or a two-dimensional Fourier spectrum. There are many commercial software programs that can do this. The current work has used the mathematical package of programs called MATLAB[2] but the results do not depend on this choice. The present study was, in part, to determine how to best analyze the two-dimensional Fourier transform of a suitable SEM target to extract some simple measure of sharpness that could be quantitatively expressed as one (or a few) numbers. The approach taken was to use statistical techniques to characterize two-dimensional Fourier spectrum density by their various moments. The second moment measures the two-dimensional spread of a probability distribution (or two-dimensional normalized FT in the present case), the third moment measures skewness, and the fourth moment (kurtosis) measures peakedness combined with tailedness. All three of these moments are potentially useful for characterizing the high spatial frequency content (e.g., determined, in part, by focus) and any isotropy that might be present (e.g., due to astigmatism). Anisotropic responses due to the SEM per se can be distinguished from any responses due to the target by repeating this analysis on images obtained after rotating the target by 90 degrees. The use of this statistical probability characterization approach will be illustrated in the following sections of this paper.

During this study, it was found that there was additional information in the tails of the two-dimensional FT where the low spatial frequency response has decreased by a factor of 100 to 1000 or more from its

peak value. This information would appear as a narrow ridge of FT amplitude rising out of the noise and approximately centered on the X- and/or Y- axis of the FT when the spectrum was viewed as a three-dimensional surface with its amplitude plotted on the Z-axis. If the X-axis is taken as the scan direction and the Y-axis as the direction of multiple scan lines, the Y-axis ridge can often be attributed to the effects of vibration (often visible in the SEM image if the magnification is high enough). The X-axis ridge, when present, was attributed to systematic variations during the scanning that repeat on every scan line. Possible sources of such variations are: 60 Hertz interference or detector inefficiencies. The use of the present FT approach to measure these X-axis effects was noted, but not pursued in the present study.

It was found that when an SEM image was generated with the occurrence of vibrations, the marginal (i.e., the one-dimensional) kurtosis along the Y-axis is much lower than that along the X-axis if the FT spectrum extends far enough into the high spatial frequency regions where these two ridges appear. Thus, the relative difference between the marginal kurtoses in this case can be used to signal the presence of vibrations. It is recommended that the vibration and/or systematic variations along the scan lines should be eliminated at the source (i.e., the SEM) and revised SEM images of the test object be obtained with no (or negligible) ridges before continuing with the present analysis.

## 4.5 Representative Results

A series of five SEM micrographs are shown as examples depicting a representative set of experiments developed to demonstrate the sharpness analysis procedure. Figure 1 is a micrograph of the grass sample taken with the SEM conditions set for the best possible image. The accelerating voltage for this series was chosen to be relatively high (15 kV) so that small changes in instrument conditions would result in obvious differences in the micrograph. Figure 2 is a similar micrograph except that some intentional defocus has been induced into the image. Note that there is a pulling or astigmatic appearance to the image. This might indicate the presence of some misalignment in the SEM column. Figure 3 is a micrograph which is properly focused, however some degree of astigmatism was intentionally induced in the image by stigmator misadjustment. Figure 4 is a high quality micrograph with external vibration induced in the image and Figure 5 is a readjustment to obtain the best quality image possible. For testing like this, it has proven valuable to begin with a good image, make a change in the instrument parameter and then return to a good image. This allows the instrument to always begin a data set at approximately the same level of performance, and it also tests the sensitivity and reproducability of the analysis program.

### 4.5.1 Kurtosis Analysis. Figure 6 is the graphical measure of sharpness following analysis of these five images. Kurtosis was calculated with the algorithm described previously. Low numbers for kurtosis indicate a better quality image or higher sharpness. Sample 1 and Sample 5 from the graph are the known good images with kurtosis values of 9.32 (Sample 1) and 9.35 (Sample 2). The visually poorer image of Sample 2 exhibits a high kurtosis figure of 9.85 and the slightly sharper image of Sample 3 has a somewhat lower kurtosis value with a figure of about 9.66. From Figure 6 it is clear that Sample 4 exhibits an extremely high sharpness value (low kurtosis number). On the surface this would imply that the image is in fact sharper. In a way, this is true because the very sharp vibration lines running through the image results in an anomalously low value for kurotsis (good sharpness). This is why we recommend

that images containing vibration be eliminated before evaluating sharpness.

**4.5.2 Marginal Kurtosis Analysis.** Figure 7 demonstrates the use of the marginal kurtosis on the data sets. It is recommended that a first pass through the data set be made by using the marginal kurtosis algorithm to eliminate anomalous data such as those seen in Figure 6, Sample 4. Anomalous data would include those images with increased vibration, increased field emission tip noise, etc. The anomalous data set becomes obvious when a study of the relative difference of marginal kurtosis is performed. Here it is clear that Sample 4 demonstrates approximately a 5x greater relative difference (0.56) as compared to the other images. Sample 4 is an indicator that something is radically wrong and service measures should be implemented. This first check can rapidly signal potential measurement problems that can interfere with subsequent measurement results.

## 5. CONCLUSION

The work presented in this paper describes a relatively simple characterization method based on the statistical analysis of Fourier transforms of SEM images. This method yields numerical and interpretable results regarding the performance of a given SEM or other similar instrument. This work has been facillitated by the use of a relatively simple, easy to fabricate test target which may become a NIST reference material, thus making it readily available for any user. The present method has been illustrated with the recommended test target by using a series of micrographs demonstrating intentionally introduced degradation of the SEM performance, and a supplememtary procedure for the elimination of anomalous data sets has been described. In conclusion, the present method has been demonstrated to be useful for monitoring the performance of manual, semi-automated and automated SEM instrumentation.

## 6.0 ACKNOWLEDGEMENTS

## 7.0 REFERENCES

1.    Contribution of the National Institute of Standards and Technology (formerly the National Bureau of Standards) Not subject to copyright.

2.    Certain commercial equipment is identified in this report to adequately describe the experimental procedure. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the equipment identified is necessarily the best available for the purpose.

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| Table 1 Some of the Contributing Factors to the SEM Image Affecting Image Sharpness |
| --- |
| Focus |
| Beam Diameter. |
| Astigmatism. |
| Beam Energy and Beam Current. |
| Scan Linearity and Scan Calibration. |
| Collector Detection Efficiency |
| Vibration of Specimen Relative to the Electron Beam. |
| Linearity and Noise Level of Video Circuity. |



15 kV     100,000x
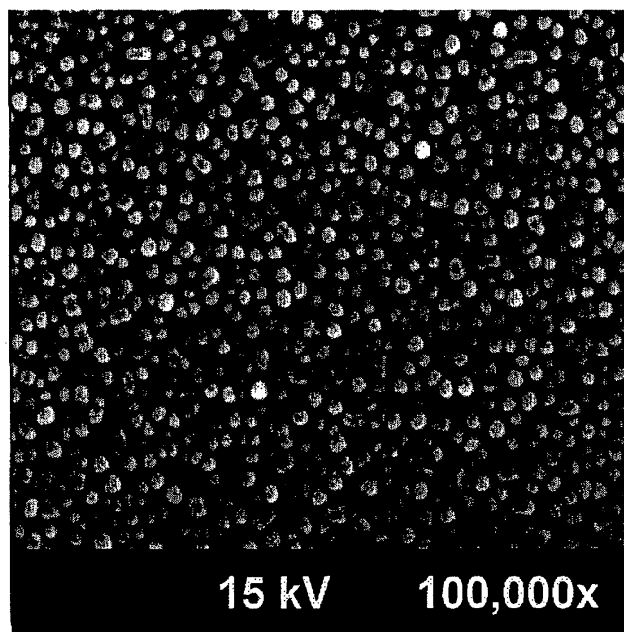
Figure 1    SEM micrograph of the "grass" sample where the instrument conditions are optimized for best performance and sharpness.
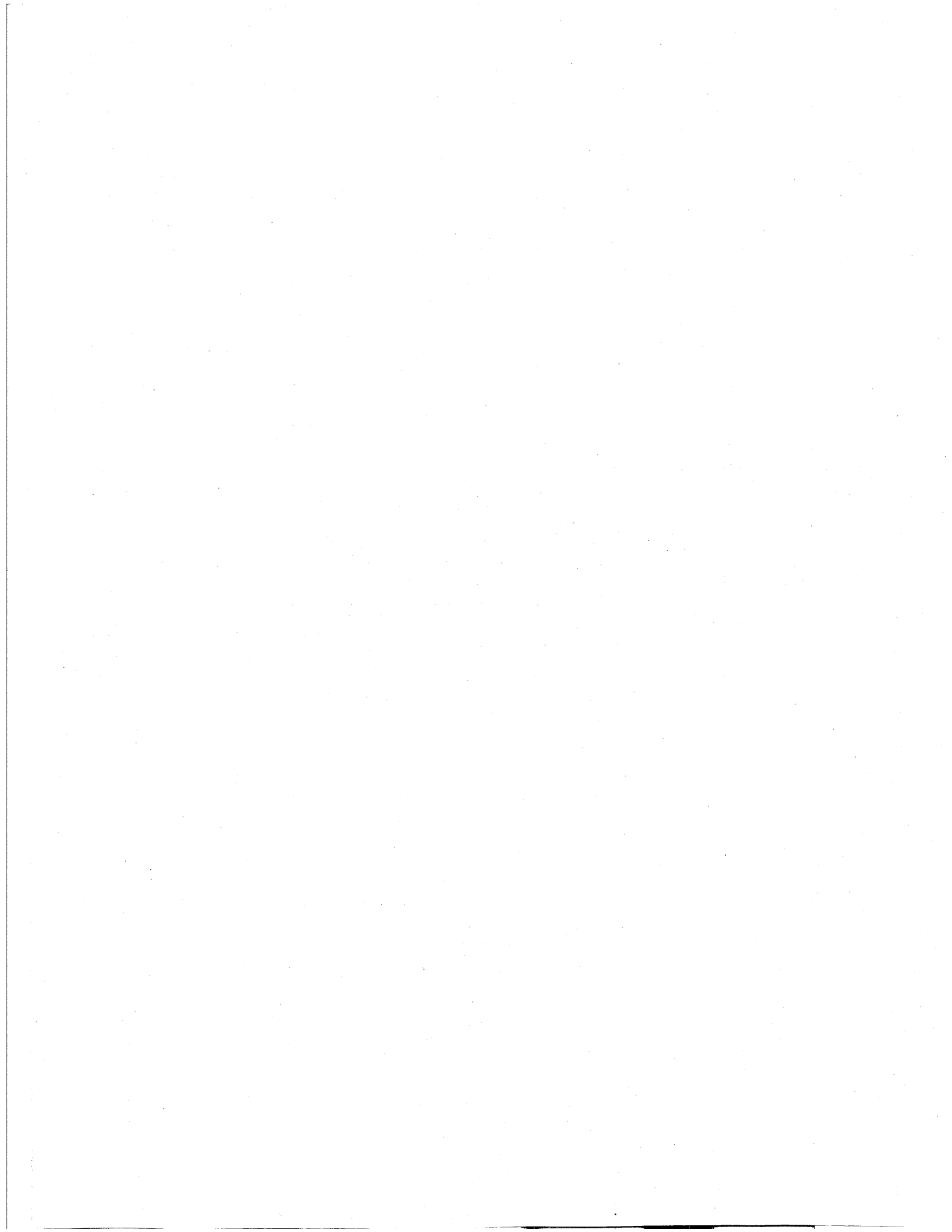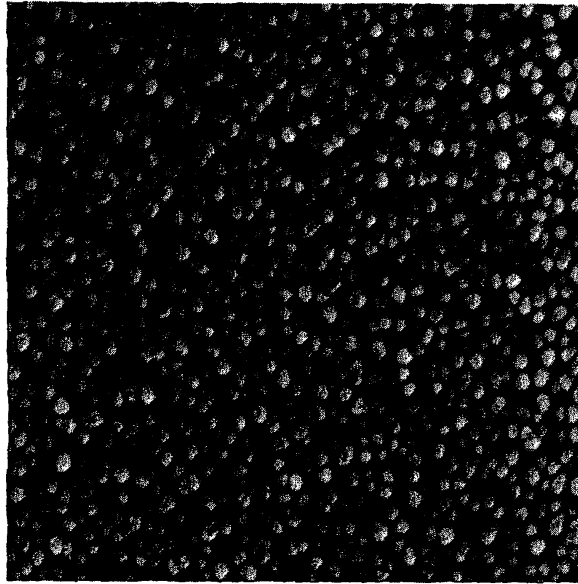
Figure 2.    SEM Micrograph with induced defocus in the image.
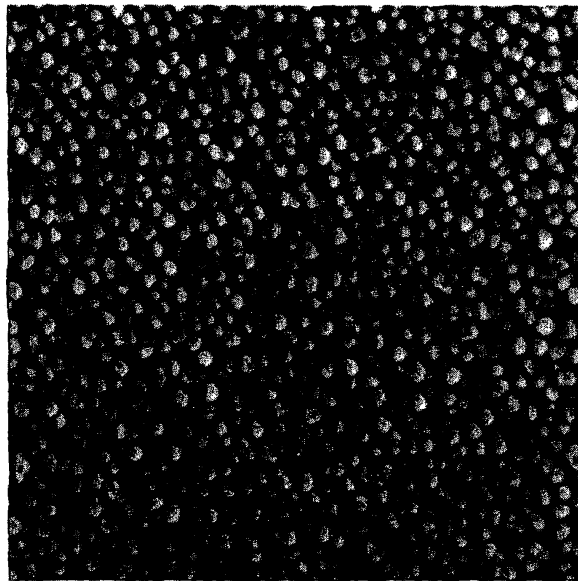


Fgure 3.    SEM Micrograph with induced astigmatism.
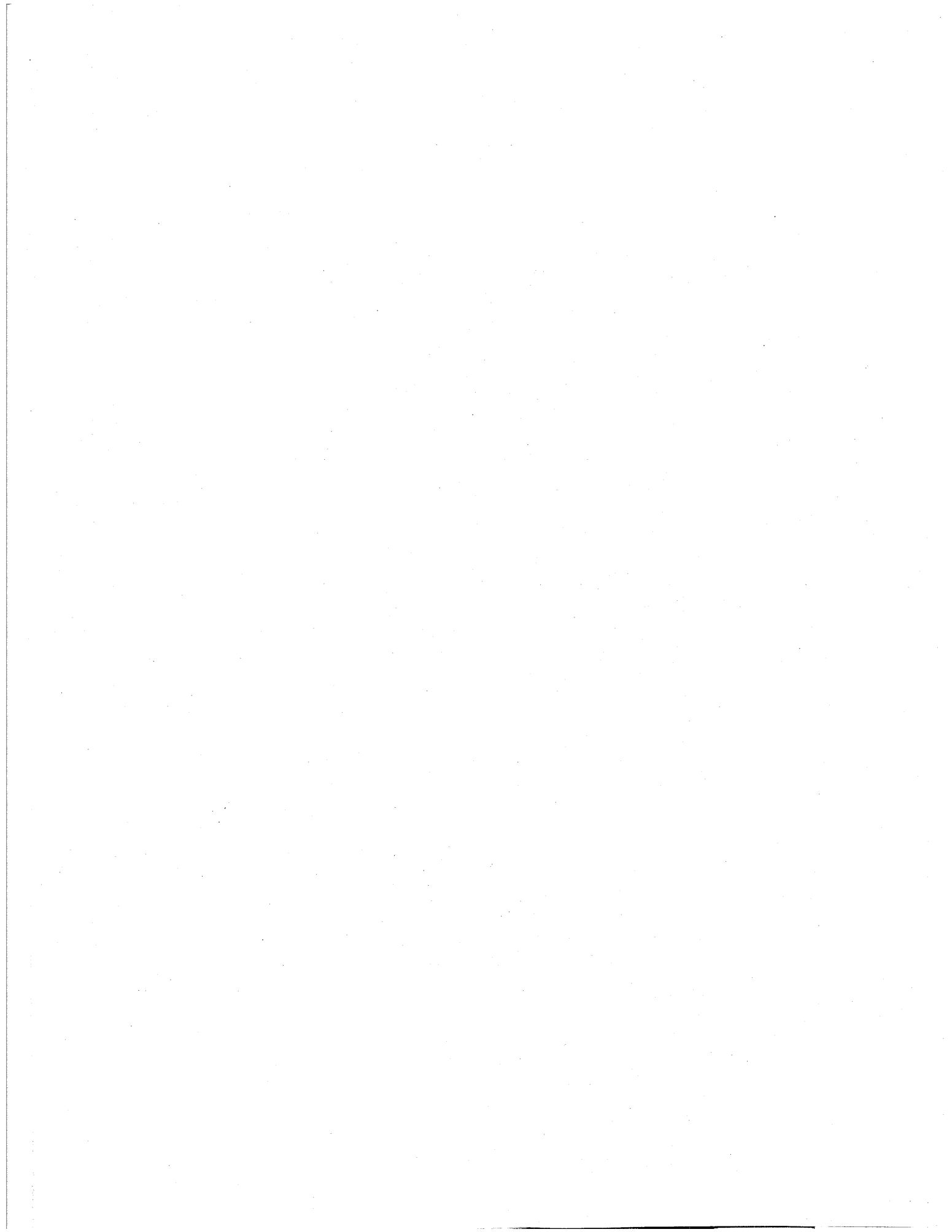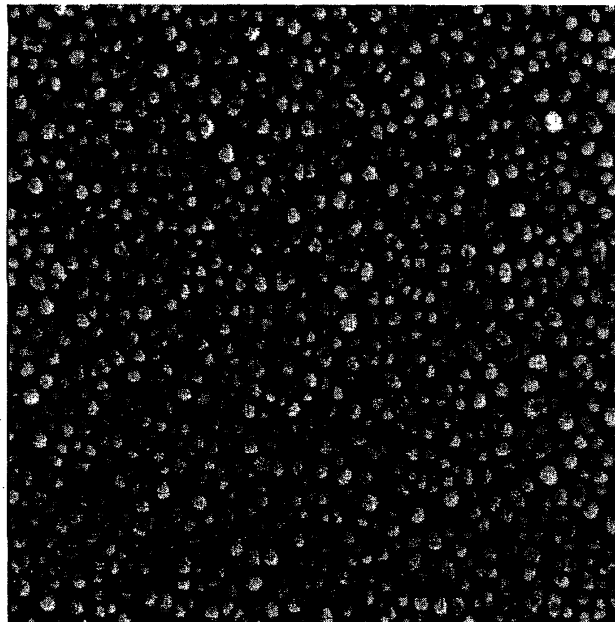
Figure 4.       SEM micrograph with vibration induced in the image.
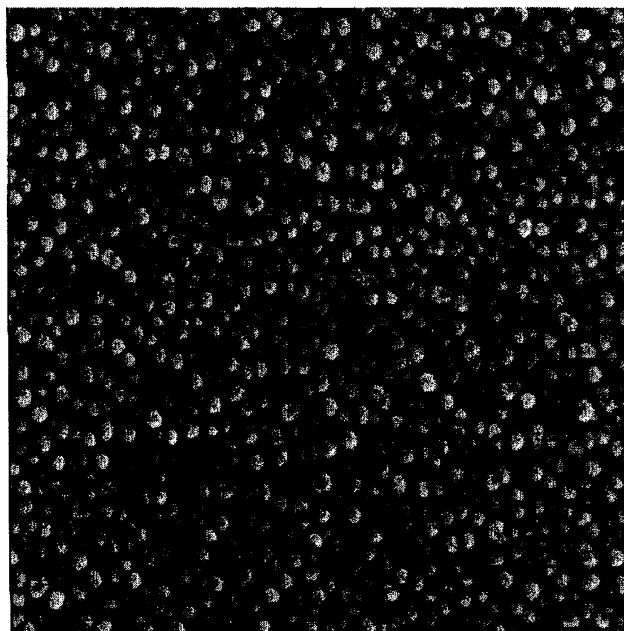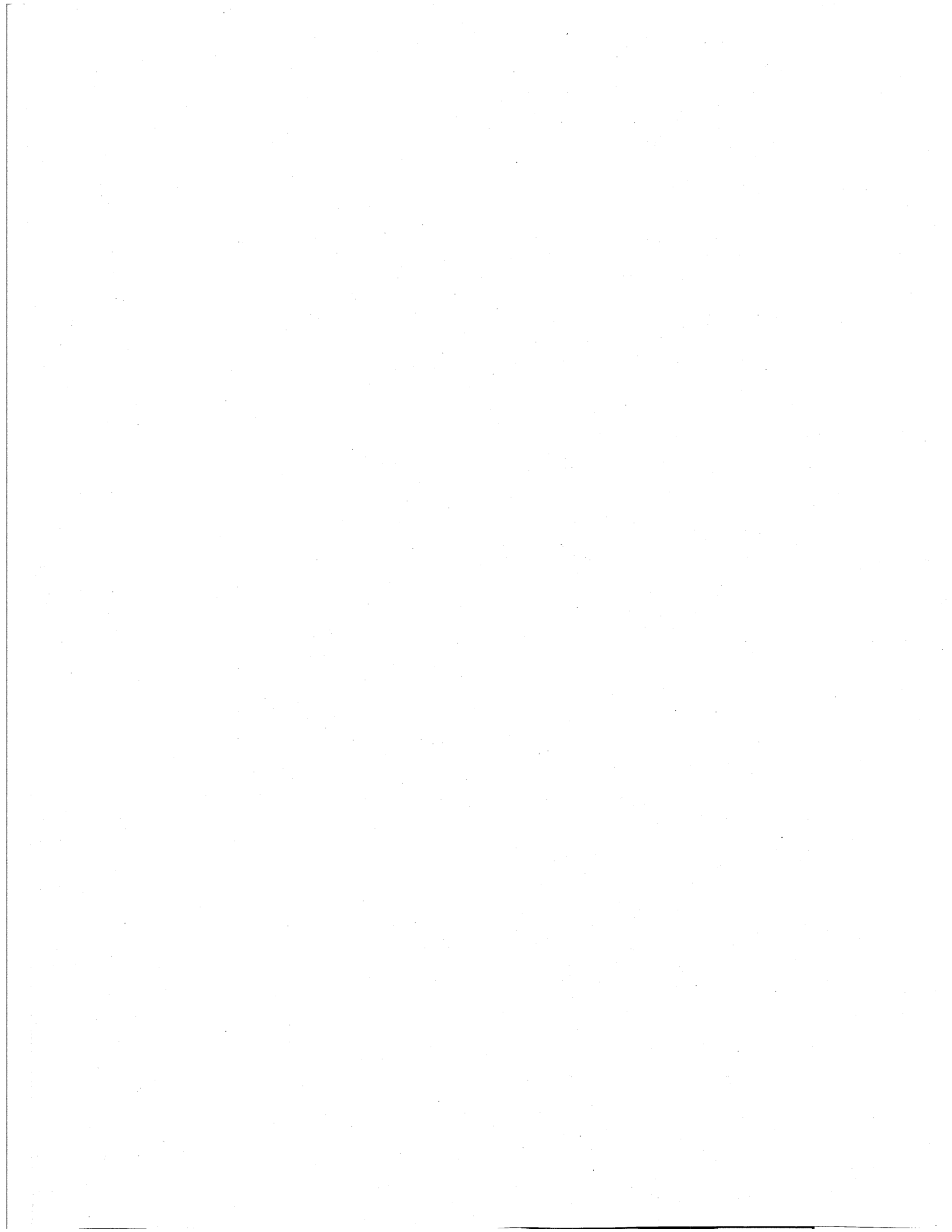


Figure 5.       SEM Micrograph with conditions returned to optimum.
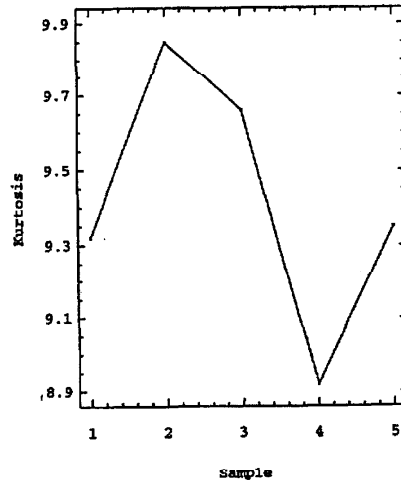
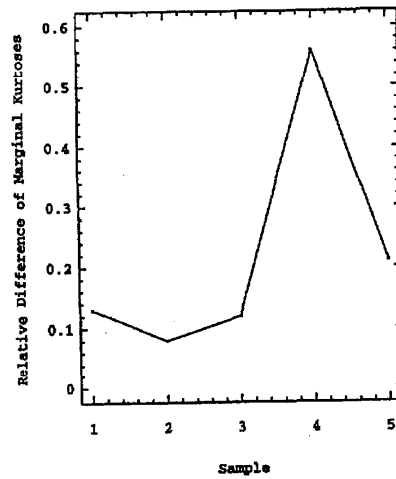Figure 6.     Calculated kurtosis values for samples 1 through 5.



Figure 7.     Relative difference of marginal kurotses for samples 1 through 5.